

Plasma induced neutrino spin-flip in a supernova and new bounds on the neutrino magnetic moment

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Abstract

The neutrino chirality-flip process under the conditions of the supernova core is investigated in detail with the plasma polarization effects in the photon propagator taken into account in a more complete form than in earlier publications. It is shown in part that the contribution of the proton fraction of plasma is essential. New upper bounds on the neutrino magnetic moment are obtained: $\mu_\nu < (0.5 - 1.1) \times 10^{-12} \mu_B$ from the limit on the supernova core luminosity for ν_R emission, and $\mu_\nu < (0.4 - 0.6) \times 10^{-12} \mu_B$ from the limit on the averaged time of the left-handed neutrino washing out. The best upper bound on the neutrino magnetic moment from SN1987A is improved by the factor of 3 to 7.

1 Neutrino spin-flip in the supernova core

Nonvanishing neutrino magnetic moment leads to various chirality-flipping processes where the left-handed neutrinos produced in the stellar interior become the right-handed ones, i.e. sterile with respect to the weak interaction. A considerable interest to the neutrino magnetic moment arised after the great event of SN1987A, in connection with the modelling of a supernova explosion, where gigantic neutrino fluxes define in fact the process energetics. It means that such a microscopic neutrino characteristic, as the neutrino magnetic moment, would have a critical influence on macroscopic properties of these astrophysical events. Namely, the left-handed neutrinos produced inside the supernova core during the collapse, could convert into the right-handed neutrinos due to the magnetic moment interaction. These sterile neutrinos would escape from the core leaving no energy to explain the observed luminosity of the supernova. Thus, the upper bound on the neutrino magnetic moment can be established.

This matter was investigated by many authors. We will mainly focus on the paper by R. Barbieri and R. N. Mohapatra [1] which now looks as the most reliable instant constraint on the neutrino magnetic moment from SN1987A, according to [2]. The authors [1] considered the neutrino spin-flip via both $\nu_L e^- \rightarrow \nu_R e^-$ and $\nu_L p \rightarrow \nu_R p$ scattering processes in the inner core of a supernova immediately after the collapse. Imposing for the ν_R luminosity Q_{ν_R} the upper limit of 10^{53} ergs/s, the authors obtained the upper bound on the neutrino magnetic moment:

$$\mu_\nu < (0.2 - 0.8) \times 10^{-11} \mu_B. \quad (1)$$

However, the essential plasma polarization effects in the photon propagator were not considered in [1], and the photon dispersion was taken in a phenomenological way, by inserting an *ad hoc* thermal mass into the vacuum photon propagator.

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A detailed investigation of this question was performed in the papers by A. Ayala, J. C. D’Olivo and M. Torres [3, 4], who used the formalism of the thermal field theory to take into account the influence of hot dense astrophysical plasma on the photon propagator. The upper bound on the neutrino magnetic moment compared with the result of the paper [1], was improved in [3, 4] in the factor of 2:

$$\mu_\nu < (0.1 - 0.4) \times 10^{-11} \mu_B. \quad (2)$$

However, the authors [3, 4] considered only the contribution of plasma electrons, and omitted the proton fraction. This is despite the fact that the electron and proton contributions to the neutrino spin-flip process were evaluated in [1] to be of the same order. Thus, the reason exists to reconsider the neutrino spin-flip processes in the supernova core more attentively, and this is the subject of this paper. Here we confirm in part, that the scattering on plasma protons is essential, as well as the scattering on plasma electrons.

2 Cherenkov process $\nu_L \rightarrow \nu_R \gamma$ and its crossing $\nu_L \gamma \rightarrow \nu_R$

Let us start from the Cherenkov process of the photon (plasmon) creation by neutrino, $\nu_L \rightarrow \nu_R \gamma$, which should be appended by the crossed process of the photon absorption $\nu_L \gamma \rightarrow \nu_R$. The Lagrangian of the interaction of a neutrino having a magnetic moment μ_ν with photons is:

$$\mathcal{L} = -\frac{i}{2} \mu_\nu (\bar{\nu} \sigma_{\alpha\beta} \nu) F^{\alpha\beta}, \quad (3)$$

where $\sigma_{\alpha\beta} = (1/2)(\gamma_\alpha \gamma_\beta - \gamma_\beta \gamma_\alpha)$, $F^{\alpha\beta}$ is the tensor of the photon electromagnetic field. For the creation process amplitude one obtains

$$\mathcal{M}_{\nu_L \rightarrow \nu_R \gamma \lambda} = \mu_\nu j_\alpha \varepsilon_{(\lambda)}^{*\alpha}, \quad (4)$$

where $\varepsilon_{(\lambda)}^{*\alpha}$ is the photon polarization vector, and j_α is the Fourier transform of the neutrino magnetic moment current,

$$j_\alpha = [\bar{\nu}_R(p') \sigma_{\mu\alpha} \nu_L(p)] q^\mu. \quad (5)$$

Here, $p^\alpha = (E, \mathbf{p})$, $p'^\alpha = (E', \mathbf{p}')$ and $q^\alpha = (\omega, \mathbf{k})$ are the four-momenta of the initial and final neutrinos and photon, respectively. Note that we use the signature $(+, -, -, -)$ for the four-metric.

For the $\nu_L \rightarrow \nu_R$ conversion width one obtains by the standard way:

$$\begin{aligned} \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}} &= \Gamma_{\nu_L \rightarrow \nu_R \gamma} + \Gamma_{\nu_L \gamma \rightarrow \nu_R} = \frac{\mu_\nu^2}{16 \pi^2 E} \int j_\alpha j_\beta^* \sum_{\lambda=t,\ell} \varepsilon_{(\lambda)}^{*\alpha} \varepsilon_{(\lambda)}^\beta Z_\gamma^{(\lambda)} \frac{d^3 p'}{E'} \\ &\times \left\{ \frac{\delta(E - E' - \omega)}{2\omega} [1 + f_\gamma(\omega)] + \frac{\delta(E - E' + \omega)}{2\omega} f_\gamma(\omega) \right\}, \end{aligned} \quad (6)$$

where $\lambda = t, \ell$ mean transversal and longitudinal photon polarizations, $f_\gamma(\omega) = (e^{\omega/T} - 1)^{-1}$ is the Bose—Einstein photon distribution function, and $Z_\gamma^{(\lambda)} = (1 - \partial \Pi_{(\lambda)} / \partial \omega^2)^{-1}$ is the photon wave-function renormalization. The functions $\Pi_{(\lambda)}$, defining the photon dispersion law:

$$\omega^2 - \mathbf{k}^2 - \Pi_{(\lambda)}(\omega, \mathbf{k}) = 0, \quad (7)$$

are the eigenvalues of the photon polarization tensor $\Pi_{\alpha\beta}$,

$$\Pi_{\alpha\beta} \varepsilon_{(\lambda)}^\beta = \Pi_{(\lambda)} \varepsilon_{(\lambda)\alpha}, \quad (8)$$

and can be found e.g. in [5].

The width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ can be rewritten to another form. Let us introduce the energy transferred from neutrino: $E - E' = q_0$, which is expressed via the photon energy $\omega(k)$ as $q_0 = \pm \omega(k)$. Then δ -functions in Eq. (6) can be rewritten,

$$\begin{aligned}\frac{\delta(q_0 - \omega(k))}{2\omega(k)} &= \delta(q_0^2 - \omega^2(k)) \theta(q_0), \\ \frac{\delta(q_0 + \omega(k))}{2\omega(k)} &= \delta(q_0^2 - \omega^2(k)) \theta(-q_0).\end{aligned}\tag{9}$$

Transforming the δ -function to have the dispersion law in the argument:

$$\delta(q_0^2 - \omega^2(k)) = \left[Z_\gamma^{(\lambda)}\right]^{-1} \delta(q^2 - \Pi_{(\lambda)}(q)),\tag{10}$$

one can see that the renormalization factor $Z_\gamma^{(\lambda)}$ is cancelled in the conversion width (6).

3 The rate of creation of the right-handed neutrino

Instead of $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$, the physical value we should be more interested in, is e.g. the right-handed neutrino flux, integrated over the initial left-handed neutrino states, i.e. the number of right-handed neutrinos emitted per unit time:

$$N_{\nu_R} = \int d n_{\nu_L} \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}} = \int \frac{d^3 p V}{(2\pi)^3} f_{\nu_L}(E) \Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}},\tag{11}$$

where $f_{\nu_L}(E) = (e^{(E - \tilde{\mu}_\nu)/T} + 1)^{-1}$ is the left-handed neutrino distribution function with the chemical potential $\tilde{\mu}_\nu$. There exists even more convenient value, the rate of creation of the right-handed neutrino ν_R , $\Gamma_{\nu_R}(E')$, with the fixed energy E' by all the left-handed neutrinos:

$$\Gamma_{\nu_R}(E') = \frac{d N_{\nu_R}}{d n_{\nu_R}}, \quad d n_{\nu_R} = \frac{d^3 p' V}{(2\pi)^3}.\tag{12}$$

Given $\Gamma_{\nu_R}(E')$, one can calculate both the right-handed neutrino flux and the right-handed neutrino luminosity.

The function $\Gamma_{\nu_R}(E')$ takes the form:

$$\begin{aligned}\Gamma_{\nu_R}(E') &= \frac{\mu_\nu^2}{16\pi^2 E'} \int \frac{d^3 p}{E} f_{\nu_L}(E) j_\alpha j_\beta^* \sum_{\lambda=t,\ell} \varepsilon_{(\lambda)}^{*\alpha} \varepsilon_{(\lambda)}^\beta \delta(q^2 - \Pi_{(\lambda)}(q)) \\ &\times \{[1 + f_\gamma(q_0)] \theta(q_0) + f_\gamma(-q_0) \theta(-q_0)\},\end{aligned}\tag{13}$$

and can be easily calculated when the function $\Pi_{(\lambda)}(q)$ is real. However, it has, in general, an imaginary part. It means, that the photon is unstable in plasma.

Nevertheless, there could be a possibility to move forward, if one would use instead of the δ -function its generalization. We suppose the generalization of the Breit—Wigner type, with the retarded functions $\Pi_{(\lambda)}(q)$:

$$\delta(q^2 - \Pi_{(\lambda)}(q)) \Rightarrow \frac{1}{\pi} \frac{-\text{Im} \Pi_{(\lambda)} \text{sign}(q_0) \epsilon_\lambda}{(q^2 - \text{Re} \Pi_{(\lambda)})^2 + (\text{Im} \Pi_{(\lambda)})^2},\tag{14}$$

where $\epsilon_\lambda = +1$ for $\lambda = t$ and $\epsilon_\lambda = -1$ for $\lambda = \ell$.

Taking into account that $f_\gamma(-q_0) = -[1 + f_\gamma(q_0)]$, one obtains

$$\text{sign}(q_0) \{ [1 + f_\gamma(q_0)] \theta(q_0) + f_\gamma(-q_0) \theta(-q_0) \} = 1 + f_\gamma(q_0),$$

and the rate of creation of the right-handed neutrino takes the form:

$$\begin{aligned} \Gamma_{\nu_R}(E') &= \frac{\mu_\nu^2}{16\pi^3 E'} \int \frac{d^3p}{E} f_{\nu_L}(E) [1 + f_\gamma(q_0)] j_\alpha j_\beta^* \\ &\times \sum_{\lambda=t,\ell} \frac{\rho_{(\lambda)}^{\alpha\beta} (-\text{Im } \Pi_{(\lambda)}) \epsilon_\lambda}{(q^2 - \text{Re } \Pi_{(\lambda)})^2 + (\text{Im } \Pi_{(\lambda)})^2}, \end{aligned} \quad (15)$$

where the polarization density matrices for the transversal and longitudinal photons are introduced:

$$\begin{aligned} \rho_{(t)}^{\alpha\beta} &= \sum_{\lambda=t_1, t_2} \varepsilon_{(\lambda)}^{*\alpha} \varepsilon_{(\lambda)}^\beta = - \left(g^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2} - \frac{\ell^\alpha \ell^\beta}{\ell^2} \right), \\ \rho_{(\ell)}^{\alpha\beta} &= - \varepsilon_{(\ell)}^{*\alpha} \varepsilon_{(\ell)}^\beta = - \frac{\ell^\alpha \ell^\beta}{\ell^2}, \quad \ell_\alpha = q_\alpha (uq) - u_\alpha q^2, \end{aligned} \quad (16)$$

u_α is the four-vector of the plasma velocity.

The structures appeared in the function $\Gamma_{\nu_R}(E')$ are called the photon spectral density functions:

$$\varrho_{(\lambda)} = \frac{2(-\text{Im } \Pi_{(\lambda)})}{(q^2 - \text{Re } \Pi_{(\lambda)})^2 + (\text{Im } \Pi_{(\lambda)})^2}, \quad (17)$$

Changing the integration variables $d^3p \rightarrow dq_0 dk$, one obtains after calculation:

$$\begin{aligned} \Gamma_{\nu_R}(E') &= \frac{\mu_\nu^2}{16\pi^2 E'^2} \int_{-E'}^{\infty} dq_0 \int_{|q_0|}^{2E'+q_0} k^3 dk f_\nu(E' + q_0) [1 + f_\gamma(q_0)] (2E' + q_0)^2 \\ &\times \left[1 - \left(\frac{q_0}{k} \right)^2 \right]^2 \left[\left(1 - \frac{k^2}{(2E' + q_0)^2} \right) \varrho_{(t)} - \varrho_{(\ell)} \right]. \end{aligned} \quad (18)$$

4 Neutrino interaction with background

Thus, a “photon” considered in the neutrino chirality flip processes $\nu_L \rightarrow \nu_R \gamma$ and $\nu_L \gamma \rightarrow \nu_R$, obviously can not be treated as a real photon. It would be more self-consistent to consider the vertex $\nu_L \nu_R \gamma^*$ in the neutrino scattering via the intermediate virtual plasmon γ^* on the plasma electromagnetic current presented by electrons, $\nu_L e^- \rightarrow \nu_R e^-$, protons, $\nu_L p \rightarrow \nu_R p$, etc., see the Feynman diagram in Fig. 1. Here, J^{em} is an electromagnetic current in the general sense, formed by different components of the medium, i.e. free electrons and positrons, free ions, neutral atoms, etc.

The technics of calculations of the neutrino spin-flip rate is rather standard. The only principal point is to use the photon propagator $G^{\alpha\beta}(q)$ with taking account of the plasma polarization effects. We take it in the form:

$$G^{\alpha\beta}(q) = \frac{i \varrho_{(t)}^{\alpha\beta}}{q^2 - \Pi_{(t)}} + \frac{i \varrho_{(\ell)}^{\alpha\beta}}{q^2 - \Pi_{(\ell)}}, \quad (19)$$

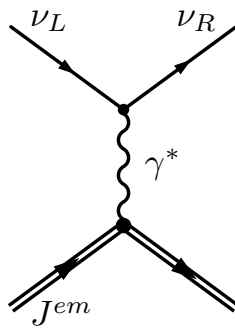


Figure 1: The Feynman diagram for the neutrino spin-flip scattering via the intermediate plasmon γ^* on the plasma electromagnetic current J^{em} .

which has no ambiguity when the functions $\Pi_{(t,\ell)}$ are real. Our generalization to the case of complex functions is based on using the same form of the propagator with the retarded functions $\Pi_{(t,\ell)}$.

Integrating the amplitude squared of the process, described by the Feynman diagram of Fig. 1, over the states of particles forming the electromagnetic current and over the states of the initial left-handed neutrinos, we obtain just the same formula (18) for the rate $\Gamma_{\nu_R}(E')$ of creation of the right-handed neutrino with the fixed energy E' .

There is also such a subtle effect as the additional energy W acquired by a left-handed neutrino in plasma. With this effect, the general expression for the rate of creation of the right-handed neutrino is:

$$\begin{aligned} \Gamma_{\nu_R}(E') &= \frac{\mu_\nu^2}{16\pi^2 E'^2} \int_{-E'}^{\infty} dq_0 \int_{|q_0|}^{2E'+q_0} \frac{dk}{k} f_\nu(E' + q_0) [1 + f_\gamma(q_0)] (2E' + q_0)^2 q^4 \\ &\times \left\{ \left(1 - \frac{k^2}{(2E' + q_0)^2} \right) \left[1 - \frac{2q_0 W}{q^2} + \frac{8E'(E' + q_0)W^2}{q^4 [(2E' + q_0)^2/k^2 - 1]} \right] \varrho_{(t)}(q_0, k) \right. \\ &\left. - \left(1 - \frac{2q_0 W}{q^2} \right) \varrho_{(\ell)}(q_0, k) \right\}, \end{aligned} \quad (20)$$

where $q^2 = q_0^2 - k^2$.

We note that our result is in agreement, to the notations, with the rate obtained by P. Elmfors et al. [6] from the retarded self-energy operator of the right-handed neutrino. However, extracting from our general expression the electron contribution only, we obtain the result which is larger by the factor of 2 than the corresponding formula in the papers by A. Ayala et al. [3, 4]. It can be seen that an error was made there just in the first formula defining the production rate Γ of a right-handed neutrino.

Our formula having the most general form, can be used for neutrino-photon processes in any optically active medium. We only need to identify the photon spectral density functions $\varrho_{(\lambda)}$. For example, in the medium where $\text{Im } \Pi_{(t)} \rightarrow 0$ in the space-like region $q^2 < 0$ corresponding to the refractive index values $n > 1$, the spectral density function is transformed to δ -function, and we reproduce the result of the paper by W. Grimus and H. Neufeld [7] devoted to the study of the Cherenkov radiation of transversal photons by neutrinos.

If one formally takes the limit $\text{Im } \Pi_{(\ell)} \rightarrow 0$, the result obtained by S. Mohanty and S. Sahu [8] can be reproduced, namely, the width of the Cherenkov radiation and absorption of longitudinal photons by neutrinos in the space-like region $q^2 < 0$. However, the limit $\text{Im } \Pi_{(\ell)} \rightarrow 0$ itself is unphysical in the real astrophysical plasma conditions considered by those authors and leads to the strong overestimation of a result.

One more unphysical case was considered in the papers by A. Studenikin et al. [9], where the additional energy W acquired by a left-handed neutrino in plasma was taken, but the photon dispersion in medium was ignored at all. The region of integration for the width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ with the fixed initial neutrino energy E was the vacuum dispersion line $q_0 = k$, see Fig. 2, left plot.

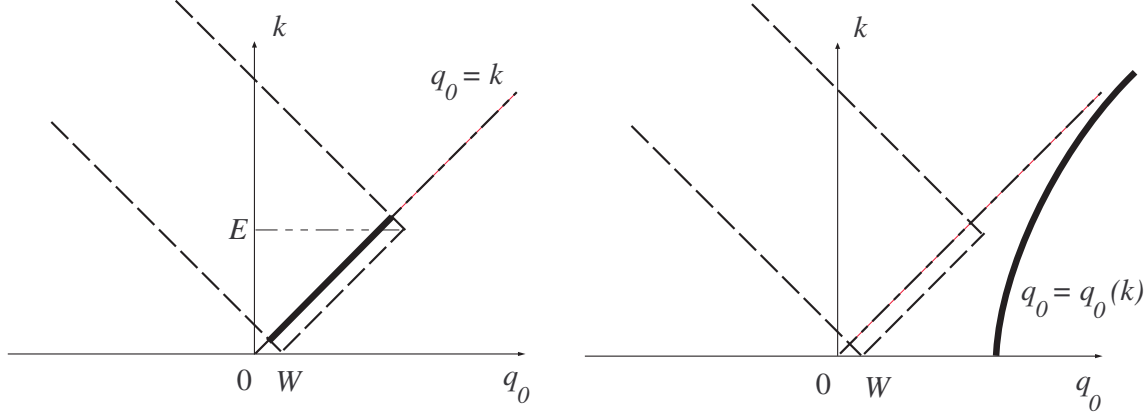


Figure 2: The region of integration for the width $\Gamma_{\nu_L \rightarrow \nu_R}^{\text{tot}}$ with the fixed initial neutrino energy E in the unphysical case when the photon dispersion in medium was ignored at all (bold line in the left plot). With the photon dispersion in account (bold line in the right plot) the threshold neutrino energy E_{min} exists for coming of the dispersion curve into the allowed kinematical region.

However, the photon dispersion in plasma is not the vacuum one, see Fig. 2, right plot. For the fixed plasma parameters, the threshold neutrino energy E_{min} exists for coming of the dispersion curve into the allowed kinematical region, as was shown in our papers [10, 11]

5 Right-handed neutrino luminosity

As it was mentioned above, an analysis of the neutrino chirality flip process has to be performed with taking account of the neutrino scattering off various plasma components: electrons, protons, free ions, etc. One can consider the contribution of the neutrino scattering off electrons into the right-handed neutrino production rate. This means that one should take into account the electron contribution only into the function $\text{Im } \Pi_{(\lambda)}$ in the numerator of the spectral density function (17). It should be stressed however, that the functions $\text{Re } \Pi_{(\lambda)}$ and $\text{Im } \Pi_{(\lambda)}$ in the denominator of Eq. (17) contain the contributions of all plasma components. At this point our result for the neutrino scattering off electrons differs from the result by A. Ayala et al. [3, 4], where the electron contribution only was taken both in the numerator and in the denominator of the plasmon spectral densities.

In the Figs. 3 and 4 we illustrate the importance of taking into account the proton contribution into the eigenvalue Π_ℓ for the longitudinal plasmon.

The details of calculations of the rate of creation of the right-handed neutrino will be published elsewhere. The results of our numerical analysis of the separate contributions of the neutrino scattering off electrons and protons, as well as the total ν_R production rate in the typical conditions of the supernova core are presented in Fig. 5.

The plotted function $F(E')$ is defined by the expression

$$\Gamma_{\nu_R}(E') = \frac{\mu_\nu^2 T^3}{32 \pi} F(E'). \quad (21)$$

It is seen from the Fig. 5 that the proton contribution is essential indeed. For comparison, the result by A. Ayala et al. [4] is also shown in Fig. 5, illustrating a strong underestimation of the neutrino chirality flip rate made by those authors.

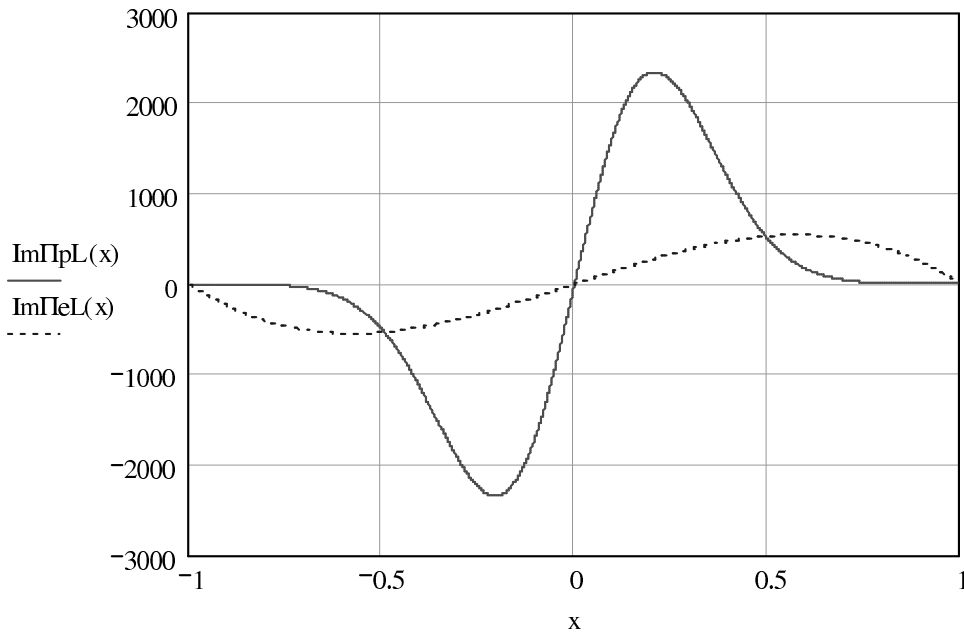


Figure 3: Proton (solid line) and electron (dotted line) contributions to the imaginary part of Π_ℓ .

The supernova core luminosity for ν_R emission can be computed as

$$Q_{\nu_R} = V \int \frac{d^3 p'}{(2\pi)^3} E' \Gamma_{\nu_R}(E'), \quad (22)$$

where V is the plasma volume.

For the same supernova core conditions as in the papers [3, 4] (plasma volume $V \sim 8 \times 10^{18} \text{cm}^3$, temperature range $T = 30 - 60 \text{ MeV}$, electron chemical potential range $\mu_e = 280 - 307 \text{ MeV}$), we found

$$Q_{\nu_R} = \left(\frac{\mu_\nu}{\mu_B} \right)^2 (0.76 - 4.4) \times 10^{77} \text{ ergs/s}. \quad (23)$$

Assuming that $Q_{\nu_R} < 10^{53} \text{ ergs/s}$, we obtain the upper limit on the neutrino magnetic moment

$$\mu_\nu < (0.5 - 1.1) \times 10^{-12} \mu_B. \quad (24)$$

6 Left-handed neutrino washing away

An additional method can be used to put a bound on the neutrino magnetic moment. Together with the supernova core luminosity Q_{ν_R} , a number of right-handed neutrinos emitted per 1 sec per 1 cm^3 can be defined via the rate $\Gamma_{\nu_R}(E')$ as

$$n_{\nu_R} = \int \frac{d^3 p'}{(2\pi)^3} \Gamma_{\nu_R}(E'). \quad (25)$$

The right-handed neutrino energy spectrum, i.e. a number of right-handed neutrinos emitted per 1 sec per 1 MeV from the unit volume, dn_{ν_R}/dE' , can be also evaluated numerically. In the Fig. 6 we show, taking for definiteness $\mu_\nu = 10^{-12} \mu_B$, the result of this calculation for two values of the plasma temperature.

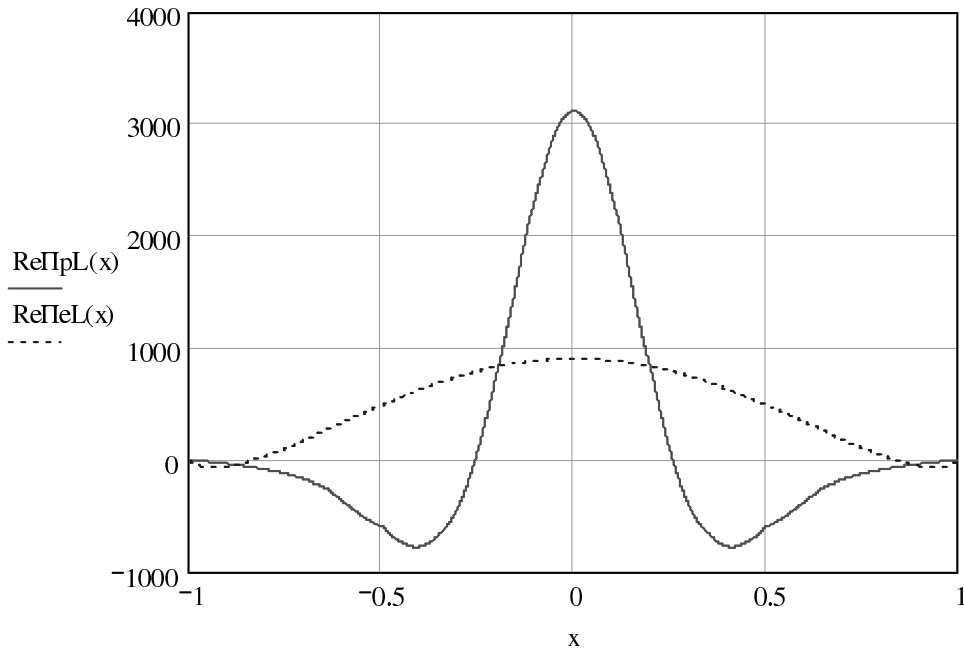


Figure 4: Proton (solid line) and electron (dotted line) contributions to the real part of Π_ℓ .

Integrating the value dn_{ν_R}/dE' over all energies, one obtains the number of right-handed neutrinos emitted per 1 cm^3 per 1 sec. Dividing this to the initial left-handed neutrino number density n_{ν_L} , one can estimate the averaged time of the left-handed neutrino washing away, i.e. of the total conversion of left-handed neutrinos to right-handed neutrinos. For the temperature range $T = 30 - 60 \text{ MeV}$, and for the electron chemical potential $\mu_e \sim 300 \text{ MeV}$, we obtain

$$\tau \simeq \left(\frac{10^{-12} \mu_B}{\mu_\nu} \right)^2 (0.14 - 0.36) \text{ sec}. \quad (26)$$

In order not to spoil the Kelvin—Helmholtz stage of the protoneutron star cooling ($\sim 10 \text{ sec}$), this averaged time of the neutrino spin-flip should exceed a few seconds. Taking the conservative limit $\tau > 1 \text{ sec}$, we obtain the bound on the neutrino magnetic moment:

$$\mu_\nu < (0.4 - 0.6) \times 10^{-12} \mu_B. \quad (27)$$

By this means, we improve the best astrophysical upper bound on the neutrino magnetic moment by A. Ayala et al. [3]. by the factor of 3 to 7.

7 Conclusions

- We have investigated in detail the neutrino chirality-flip process under the conditions of the supernova core. The plasma polarization effects caused both by electrons and protons were taken into account in the photon propagator. The rate $\Gamma_{\nu_R}(E')$ of creation of the right-handed neutrino with the fixed energy E' , the energy spectrum, and the luminosity have been calculated.
- From the limit on the supernova core luminosity for ν_R emission, we have obtained the upper bound on the neutrino magnetic moment $\mu_\nu < (0.5 - 1.1) \times 10^{-12} \mu_B$.
- From the limit on the averaged time of the neutrino spin-flip, we have obtained the upper bound $\mu_\nu < (0.4 - 0.6) \times 10^{-12} \mu_B$.
- We have improved the best astrophysical upper bound on the neutrino magnetic moment by the factor of 3 to 7.

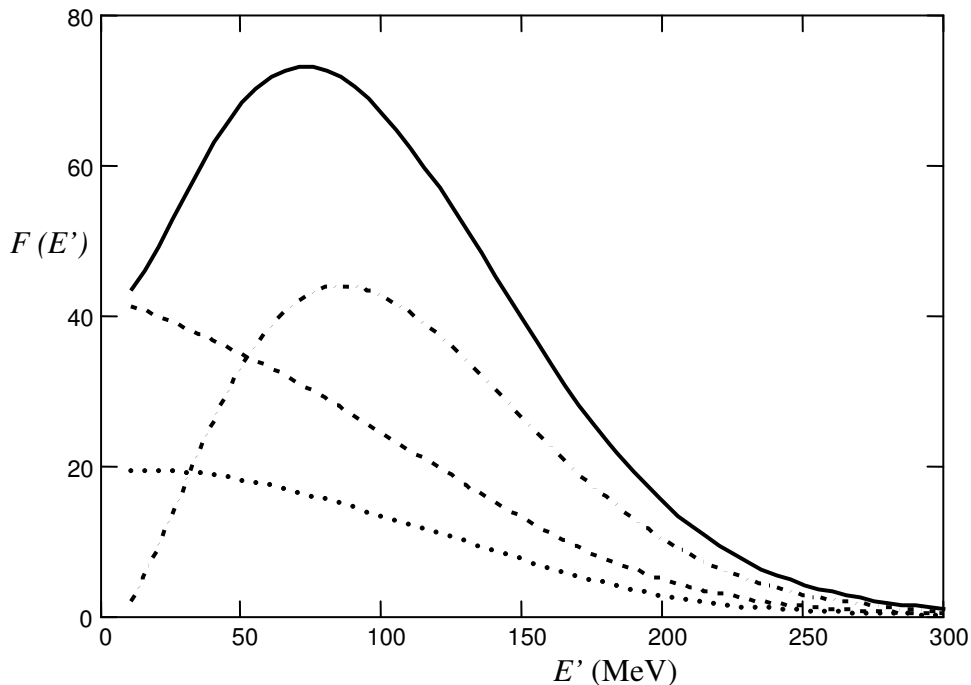


Figure 5: The function $F(E')$ defining the electron contribution (dashed line), the proton contribution (dash-dotted line) into the ν_R production rate, and the total rate (solid line) for the plasma temperature $T = 30$ MeV. The dotted line shows the result by A. Ayala et al. [4].

Acknowledgements

A. K. expresses his deep gratitude to the organizers of the XIV-th International Baksan School “Particles and Cosmology” for warm hospitality.

The work was supported in part by the Council on Grants by the President of Russian Federation for the Support of Young Russian Scientists and Leading Scientific Schools of Russian Federation under the Grant No. NSh-6376.2006.2 and by the Russian Foundation for Basic Research under the Grant No. 07-02-00285-a.

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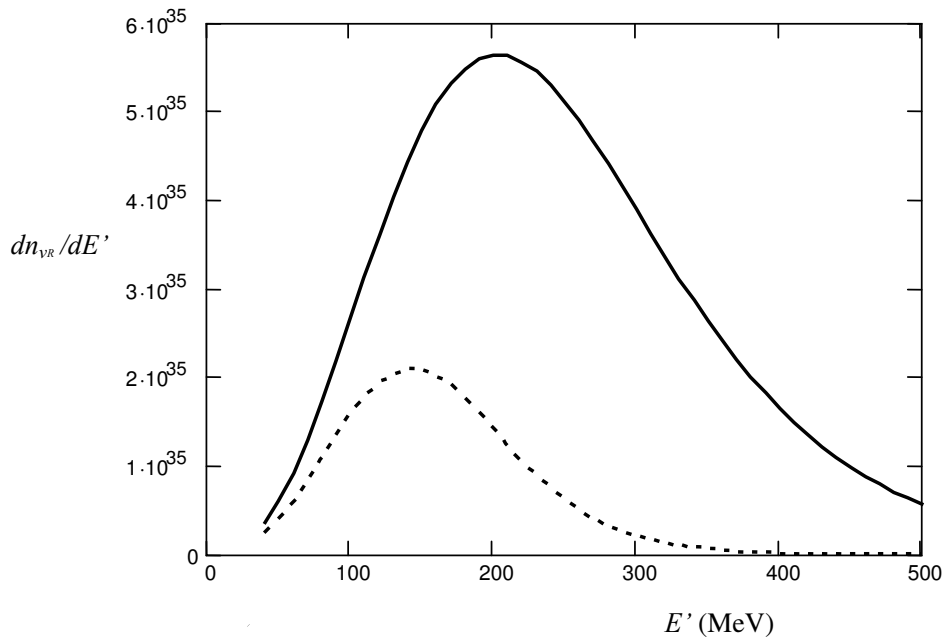


Figure 6: The number of right-handed neutrinos (for $\mu_\nu = 10^{-12} \mu_B$) emitted per 1 cm³ per 1 sec per 1 MeV of the energy spectrum for the plasma temperature $T = 60$ MeV (solid line) and for $T = 30$ MeV (dashed line).

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